REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. **PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.**

1. REPORT DATE (DD-MM-YYYY) June 2014	2. REPORT TYPE Briefing Charts	3. DATES COVERED (From - To) June 2014- July 2014

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER In-House
Interpretation of Core Length in Shear Coaxial Rocket Injectors from X-ray Radiography Measurements	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)	5d. PROJECT NUMBER
S.A. Schumaker, A.L. Kastengren, M.D.A. Lightfoot and S.A. Danczyk	5e. TASK NUMBER
	5f. WORK UNIT NUMBER QOX3

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NO.
Air Force Research Laboratory (AFMC) AFRL/RQRC 10 E. Saturn Blvd Edwards AFB CA 93524-7680	

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
Air Force Research Laboratory (AFMC) AFRL/RQR 5 Pollux Drive. Edwards AFB CA 93524-7048	11. SPONSOR/MONITOR'S REPORT NUMBER(S) **AFRL-RQ-ED-VG-2014-211**

12. DISTRIBUTION / AVAILABILITY STATEMENT
Distribution A: Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES
Briefing Charts presented at 50th AIAA/ASME/ASE/ASEE Joint Propulsion Conference, Cleveland, OH, 29 July 2014. PA#14365

14. ABSTRACT
   Shear coaxial injectors are so named because they rely on the shear between an outer lower-density high-velocity annulus and a higher-density low-velocity inner jet to atomize and mix a liquid and a gas. These injectors have an intact core, and the high amount of scatter its corrugated surface produces creates large optical densities. These high optical densities, in turn, make interrogation of the spray field in the region of the core difficult. In combustion applications, such as rockets, this region is also the area of flame holding, so is of primary importance in predicting combustion behavior. To overcome the problems of multiple scattering, the near-injector region was studied using X-ray radiography at Argonne National Laboratory's Advanced Photon Source. These results clearly show regions of differing behavior throughout the downstream distance examined. These regions correspond to changes in atomization behavior and can be used to quantify "core length" and understand more clearly what this term means. Three methods are explored to measure core length from X-ray radiography data and are compared to two-phase core length measurements from the literature. The core length nondimensionalized by the inner jet diameter was found to scale with the momentum flux to the -0.66 power.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Alex Schumaker
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified	SAR	21	19b. TELEPHONE NO (include area code) 661-275-5165

Standard Form
298 (Rev. 8-98)
Prescribed by ANSI
Std. 239.18

Interpretation of Core Length in Shear Coaxial Rocket Injectors from X-ray Radiography Measurements

S. Alexander Schumaker[1], Alan L. Kastengren[2],
Stephen A. Danczyk[1], Malissa D.A. Lightfoot[1]

[1]Air Force Research Laboratory, Edwards AFB, CA, USA
[2]Argonne National Laboratory, Argonne, IL, USA

Motivation

- **To better understand the near injector atomization of shear coaxial jets by making quantitative measurements of projected density**
  - Use quantitative centerline profiles to define atomization regions
  - Quantify "core lengths" and compare with core length data from the literature

- **Near-field region of shear coaxial sprays is optically dense limiting diagnostics**

- **X-ray radiography has developed over the past 12 years from a proof-of-concept measurement to a well-developed diagnostic technique**
  - Used to study diesel, swirl, gas-centered swirl-coaxial, impingers, and aerated liquid jet injectors

- **Use a monochromatic beam of X-rays at a synchrotron X-ray source to probe spray flowfield**
  - Main interaction is absorption, not scattering
  - Mass based: insensitive to liquid-gas interfaces
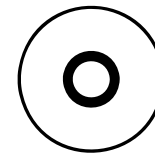
Shear Coaxial Injectors

- **Shear coaxial jets can be found in a number of combustion devices**
  - Turbofan engine exhaust, air blast furnaces, and liquid rocket engines
- **Substantial fundamental research exists on single phase coaxial jets**
  - Quantitative mass distributions measured using PLIF and anemometry
  - Includes the case where both fluids are supercritical
  - Common in modern boost-class liquid rocket engines
- **Current focus is on two-phase coaxial jets for rocket engine applications**
  - Common in upper-stage engines and during throttled conditions, startup and shutdown transients of boost-class engines
  - Previous scaling efforts have been largely based on imaging of the liquid core
- **Gaseous high speed outer jet (fuel) is used to fragment a dense liquid core (oxidizer)**
  - Fuel is typically H_2 or CH_4 and oxidizer is LOX
  - For the current study liquid H_2O and gaseous N_2 are used as surrogates for oxidizer and fuel respectively

Injector Geometries

- **Three injector geometries were used**
  - SC4 & SC24 have the same inner jet geometry (D_l & T_p) but different area ratios
  - SC1 has a similar area ratio to SC4 but has a thickened injector post
- **Injector was tested in a horizontal configuration**
 - Injector face is sloped away from the center jet
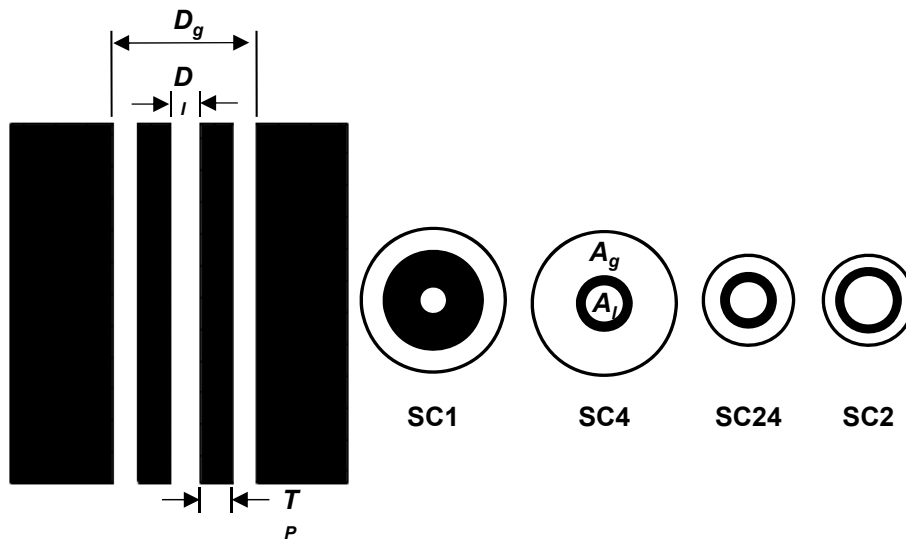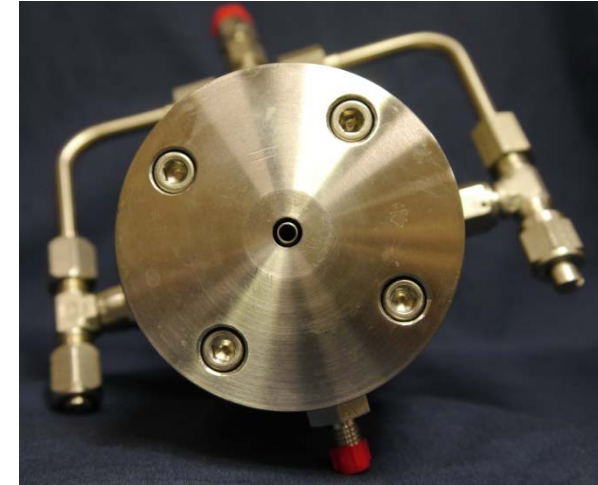
Injector	D_l (mm)	D_g (mm)	T_p (mm)	L_l/D_l	T_p/D_l	A_g/A_l
SC1	2.08	10.2	2.32	48.8	1.12	13.4
SC2	3.61	6.35	0.432	28.2	0.120	1.56
SC4	2.79	10.2	0.457	36.4	0.164	11.5
SC24	2.79	6.35	0.457	36.4	0.164	3.40

Controlling Parameters and Regimes

- **Previous studies indicate two-phase coaxial jet atomization is controlled by 6 nondimensional parameters**

  - Liquid and gas Reynolds number (Re), Ohnesorge number (Oh), Weber number (We), momentum flux ratio (Φ), and mass flux ratio (m)

  - J defined gas to liquid and m liquid to gas

- **Test conditions all in the fiber type atomization regime (red points)**

- **Since test conditions are in the fiber type regime Φ and m are the controlling parameters**

  - J controls primary atomization

  - m effects far field momentum transfer and degree of interaction between shear layers

  - Area ratio effects are accounted for in m
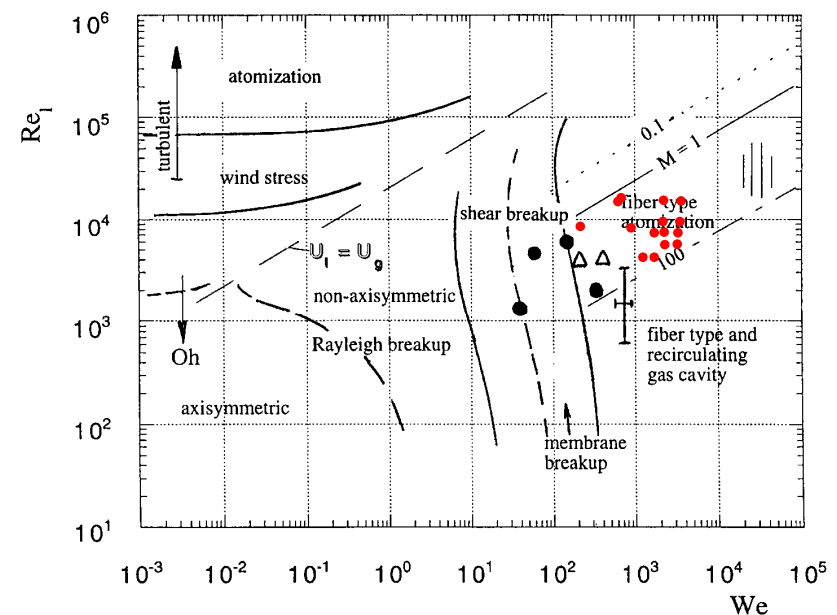
Regime Diagram: *Lasheras, J.C., and Hopfinger, E.J. Annual Review of Fluid Mechanics 32:275-308 (2000).*

Test Matrix

- **Test conditions based on 5 nominal Φ conditions (0.5, 2, 5, 10, & 15)**
  - Gas velocities (U_g): 81-229 m/s, liquid velocities (U_l): 2.0-6.0 m/s
  - Weber #: 211-2260, Reynolds #: Gas: 8,900-52,000 & Liquid: 4,200-16,500

- **SC4 and SC24 have the same inner jet geometry and use similar velocities at each Φ conditions, therefore, the 3.4 factor in m between SC4 and SC24 is due solely to the difference in area ratio**
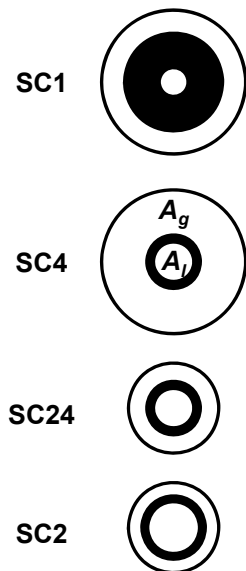
Condition	Φ	U_g (m/s)	U_l (m/s)	$\dot{m}_g$ (g/s)	$\dot{m}_l$ (g/s)	m	We	Re_g	Re_l
SC1-0.5	0.46	81	4.0	4.16	13.6	3.27	211	8,920	8,370
SC1-2	1.9	162	4.0	8.53	13.6	1.59	872	18,800	8,260
SC1-5	4.8	220	3.5	12.0	11.8	0.98	1667	27,600	7,290
SC1-10	9.6	182	2.0	9.62	6.79	0.71	1100	21,400	4,210
SC1-15	14	219	2.0	12.0	6.79	0.57	1651	27,300	4,240
SC4-0.5	0.49	125	6.0	9.85	36.7	3.72	673	25,800	15,700
SC4-2	2.0	229	5.5	18.4	33.6	1.82	2310	50,600	14,500
SC4-5	4.8	224	3.5	18.5	21.4	1.16	2260	51,800	9,150
SC4-10	9.1	219	2.5	18.4	15.4	0.84	2200	52,000	7,050
SC4-15	15	224	2.0	18.4	12.0	0.65	2250	51,400	5,590
SC24-0.5	0.46	120	6.0	2.88	36.7	12.7	635	10,400	16,500
SC24-2	1.8	212	5.6	5.40	34.3	6.34	2104	20,100	16,000
SC24-5	4.6	210	3.5	5.51	21.4	3.88	2120	21,000	9,340
SC24-10	8.7	211	2.5	5.44	15.4	2.83	2110	20,400	7,310
SC24-15	15	213	2.0	5.48	11.9	2.18	2140	20,700	5,550

SC1

A_g
A_l

SC4

SC24

SC2

Experimental Method

- **Performed at 7BM Beamline of the Advanced Photon Source**
- **Focused beam in raster-scan mode**
  - 1D transverse scans at 8 location
  - Scans perpendicular to injector axis
  - Scans collinear to injector axis
- **Beam size 7 x 8 µm FWHM**
  - Beam Photon Energy: 10keV
- **Each point averaged for 5 seconds**
- **Time resolved data taken simultaneously**
  - Used for RMS calculations
- **Beer's law to convert x-ray transmission to mass/area in beam**
- **H_2O absorption coefficient at 10keV: 5.33 cm²/g**

Near Injector Optics Layout
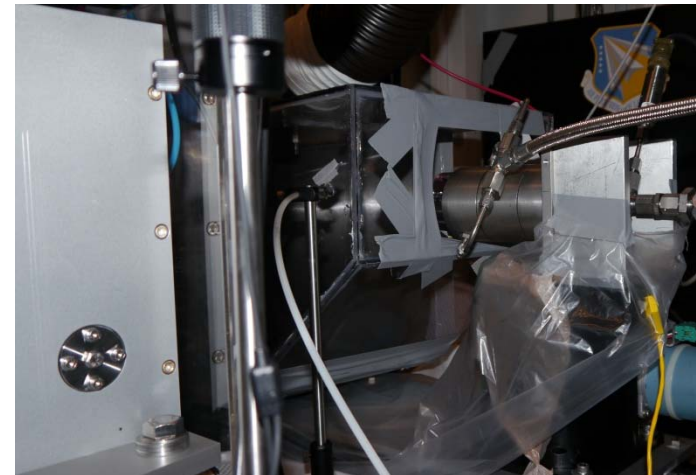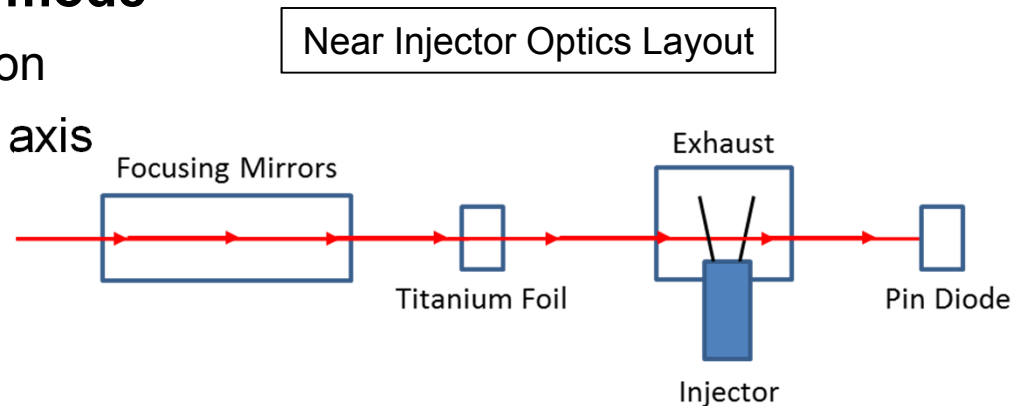
Mobile Flow Laboratory

- **Self contained mobile system capable of delivering up to one kg/s of H_2O & GN_2 at pressures in excess of 200 atmospheres**
  - Requires only power, LN_2, and exhaust from host facility.
  - System fully rated to 408 atm (Allows more GN_2 storage)
  - Dedicated Allen-Bradley control & Pacific Instruments data acquisition systems
  - Remote operation
  - High speed abort system on all data channels for added pressure safety
  - System is on wheels and can be assembled in under 2 days
  - Ran almost continuously (20 hours/day) for two weeks

Radial EPL Profiles

- **Near-injector EPL profiles have elliptical shape expected from a solid liquid jet**

- **Closest measurements were made 0.02 mm downstream**

- **EPL decreases axially as liquid core is atomized and droplets are accelerated**
  - EPL is a function of local mass flux and velocity

$$EPL \sim \frac{\Phi L_P}{U_l \rho_l}$$

- **Shoulders on SC1-10 profiles due to a liquid in the post tip recirculation zones**
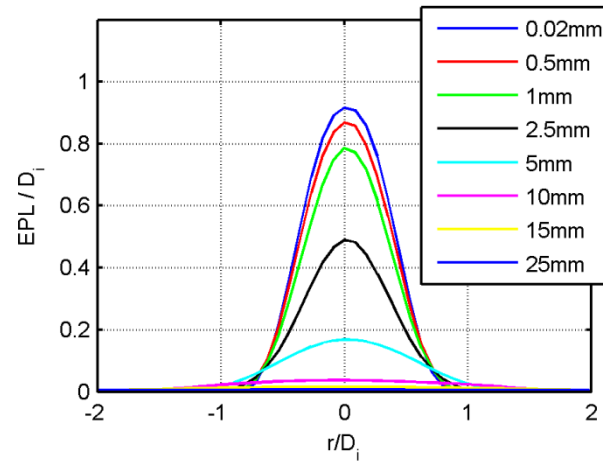
SC4-10, *J*=9.1
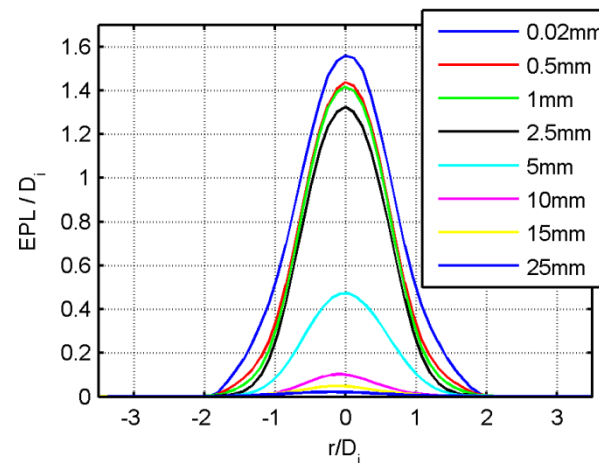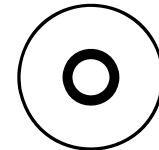
SC1-10, *J*=9.6
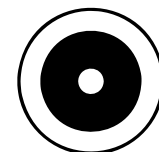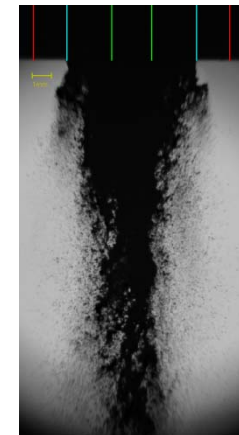
Mass Averaged Velocity

- **Obtained by dividing liquid mass flow rate by the integral of the radial liquid density profile**

- **m can have a significant effect on the velocity in the far field**

  – Comparing SC4 (m=0.84) and SC24 (m=2.83) for Φ=10; increase in m is sufficient to decrease U_{ma} from 23 m/s to 45 m/s

- **Liquid mass in the recirculation zones of SC1 results in U_{ma} values below exit velocity**

J=0.5

J=5.0

SC1

SC4

SC24
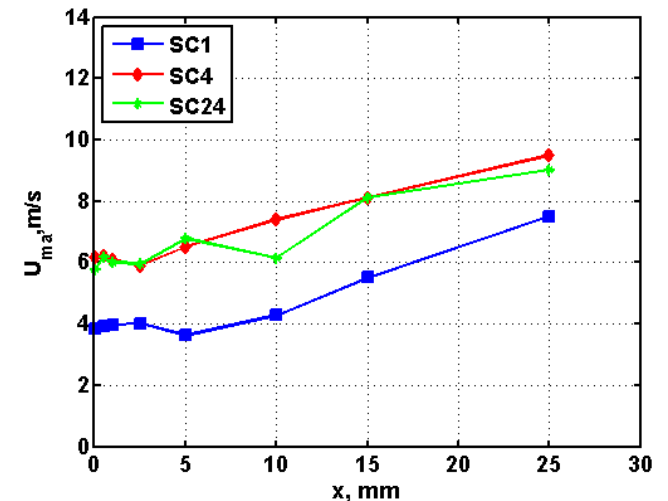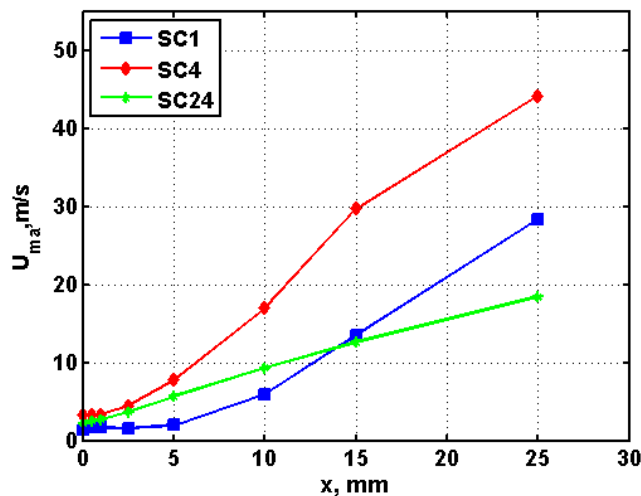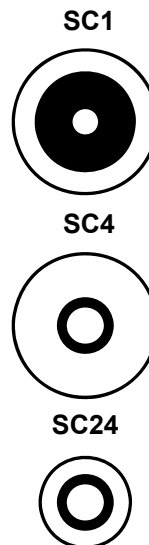
J=10
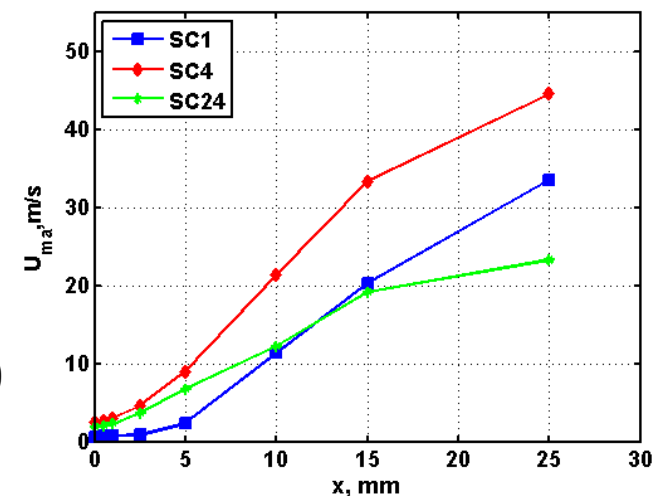
Centerline EPL Profiles

- **Centerline EPL profiles shows same general trend reported in studies of the dark core length**

  – Increasing Φ accelerates primary atomization, thus shorting the liquid core

  – The shorting of the primary atomization region is observable from the decrease in the initial slope of the centerline EPL profiles

- **Normalized centerline profiles show expansion and contraction of the liquid core at injector exit for low _J_ values (0.49 & 2)**
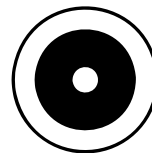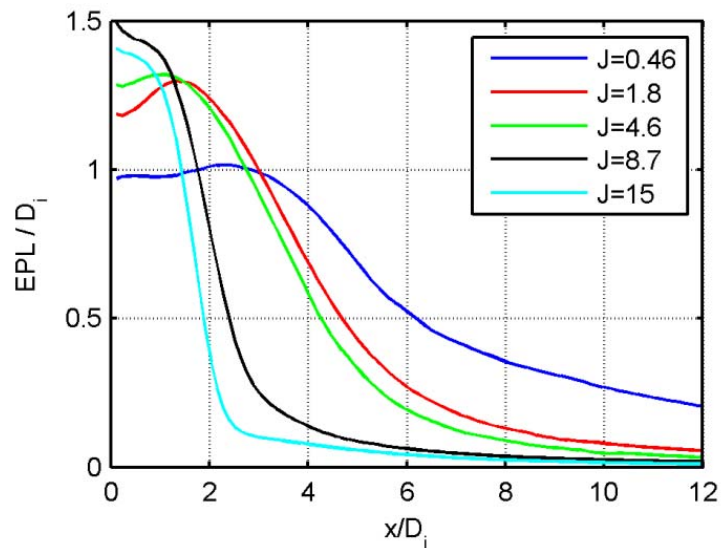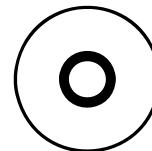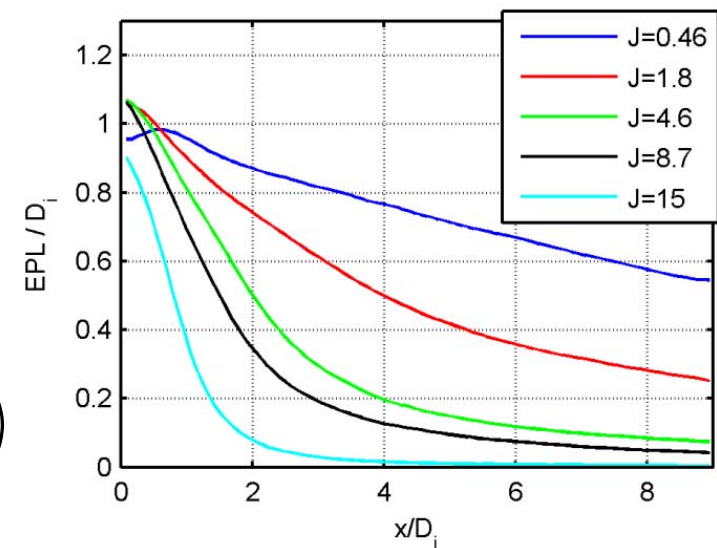
Atomization Regions

- **Centerline EPL profiles can be used to identify four hypothetical spray regions**

  - **Near-Injector Region:** Characterized by either a constant or slight increase in the centerline EPL following the injector exit

  - **Primary Atomization / Core Breakup Region:** Characterized by a nearly linear decline in EPL

  - **Transition Region:** Characterized by a clear change in slope in the centerline Profiles

  - **Far-Field Region**: Characterized by a continuing drop in EPL as the spray widens, secondary atomization decreases droplet size and droplet velocity continues to slowing increase

- **What is the best method to measure core length from Centerline EPL profile? How do these core length measurements compare to backlit core lengths?**
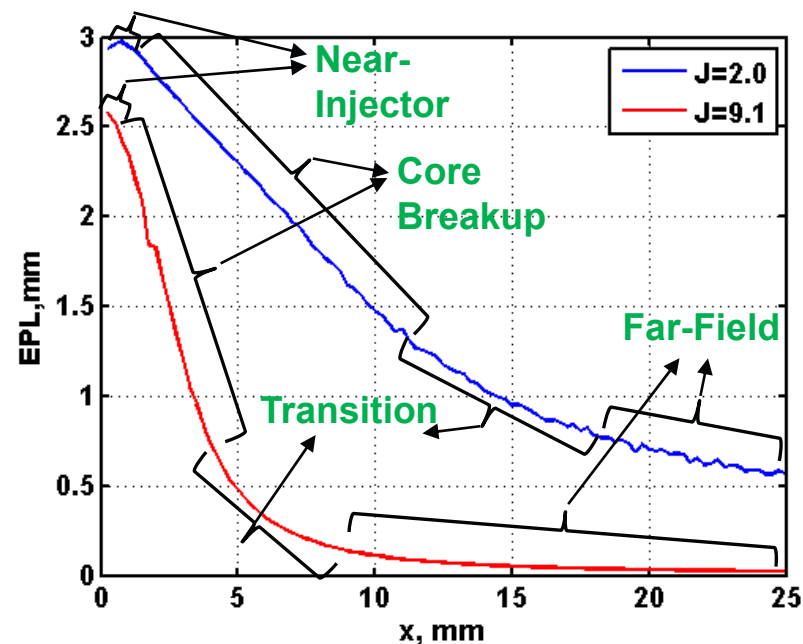
Core Length Definitions

- **Three methods explored to measure core length from EPL data**
  - Percent decrease in EPL
  - Change in slope by calculating 1st spatial derivative
  - Peak EPL RMS

- **Percent Decrease in EPL**
  - After normalization it can be uniformly applied to all conditions and geometries
 - Theory does not provide a meaningful percent decrease
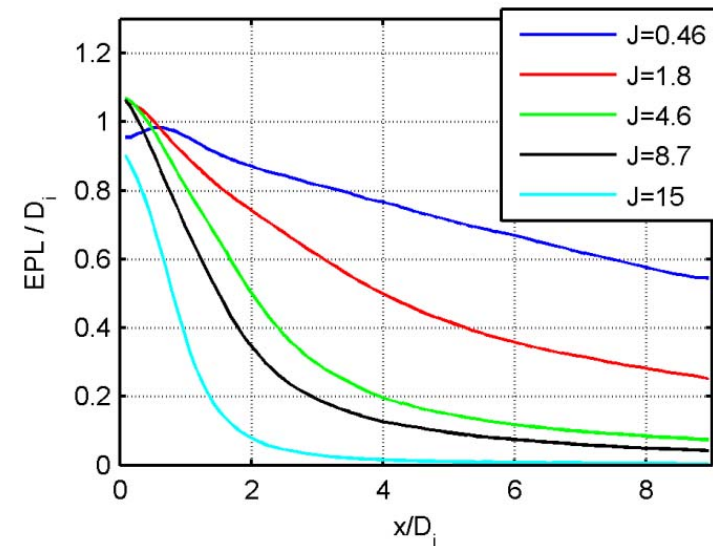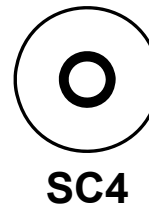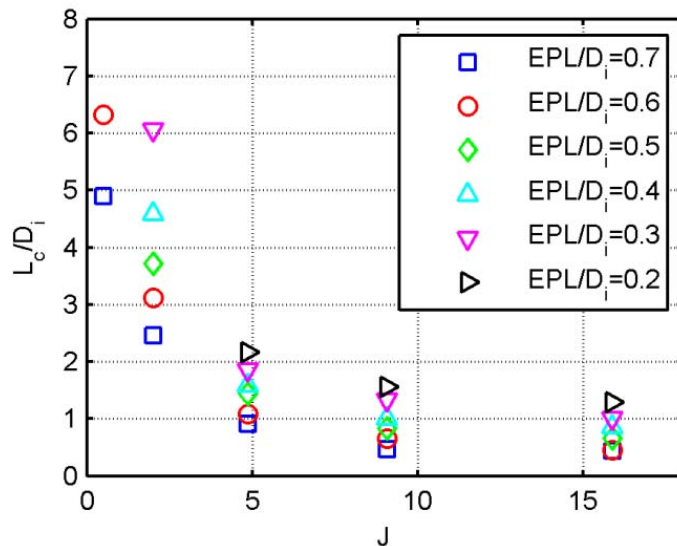
Core length: Spatial Derivative

- **Goal: use spatial derivative to capture change in slope at start of transition region**

  - Can be sensitive and noisy when applied to experimental data

  - Data was smoothed prior to taking the derivative

 - Unable to capture end of the core but was able to capture the start of the far-field

SC2

SC1

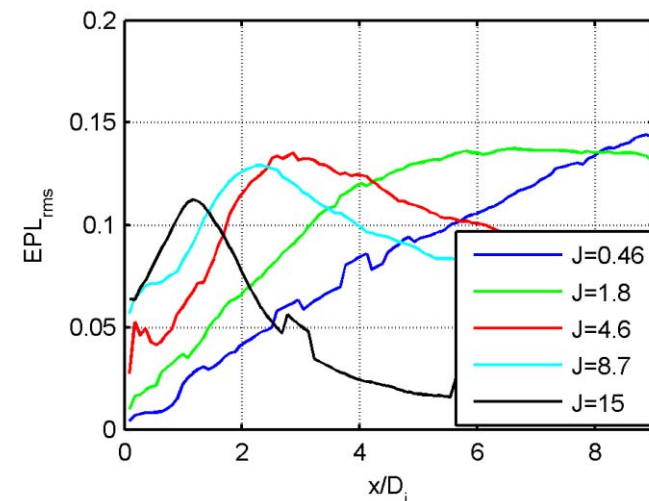**SC24**
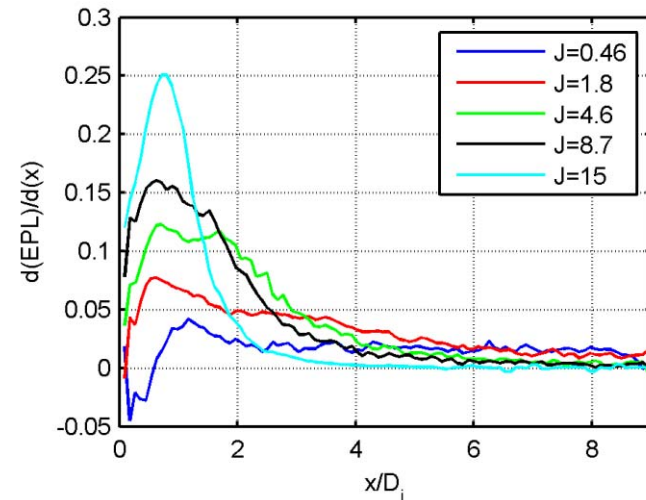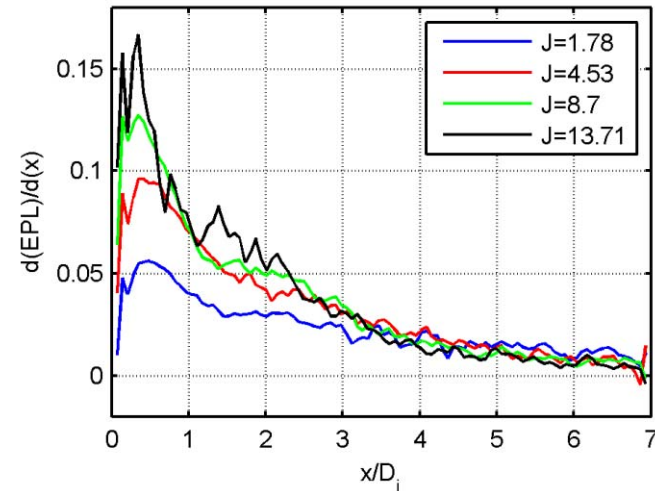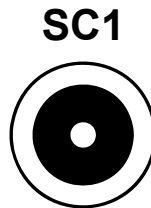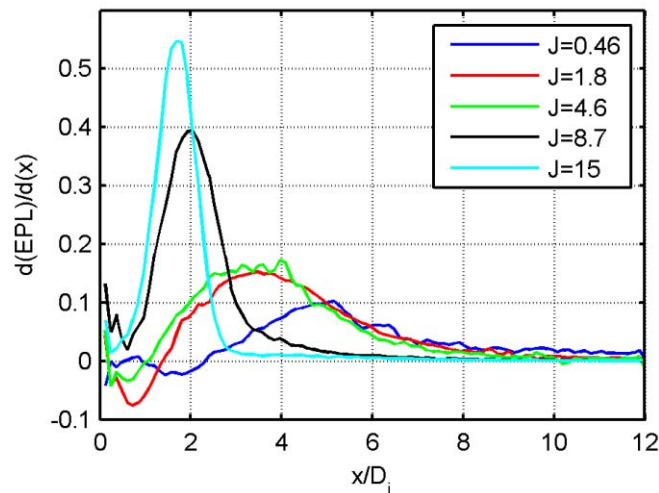
Core length: Peak EPL RMS

- **Use peak EPL RMS as marker for core tip**

  - Due to dependence on mass flux and velocity dynamic slow moving liquid structures with high mass flux

  - On centerline it is hypothesized that the peak RMS corresponds with core tip

- **Peak RMS core lengths found to agree well with *EPL/D$_i$=0.3* core lengths**

SC4
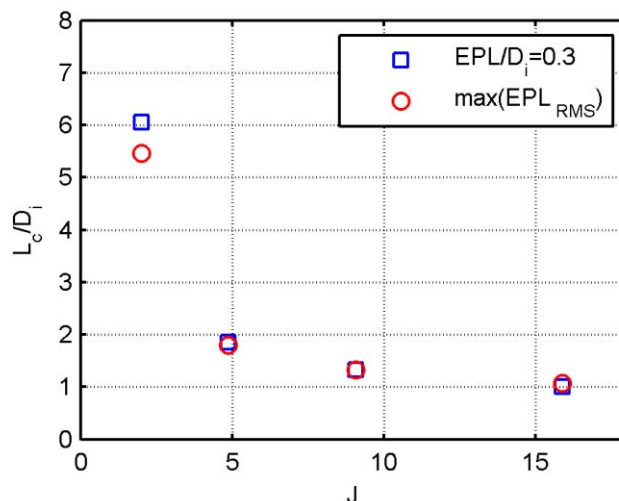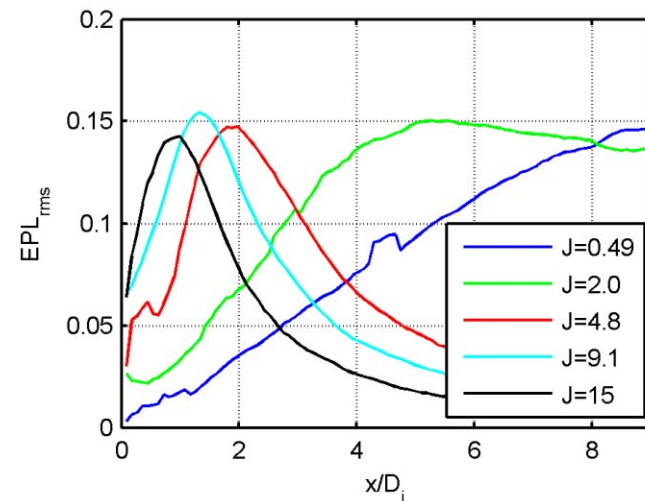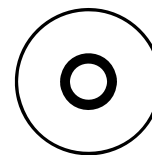
SC24

Core Length Comparison

- **Current core length data ($EPL/D_i=0.3$) was compared to three two-phase shear coaxial studies from the literature**

  – Woodward et. al. (1994): N_2 & H_2O, Laboratory source X-ray radiography with a time-averaged thresholding method

  – Eroglu et. al. (1991): Air & H_2O, Backlit imaging with an instantaneous thresholding method.

  – Leyva et. al. (2007): GN_2 & LN_2, Backlit imaging with an instantaneous thresholding method.

- **Fit from Leyva et. al.**

  – Between $18J^{-0.2}$ & $26J^{-0.2}$

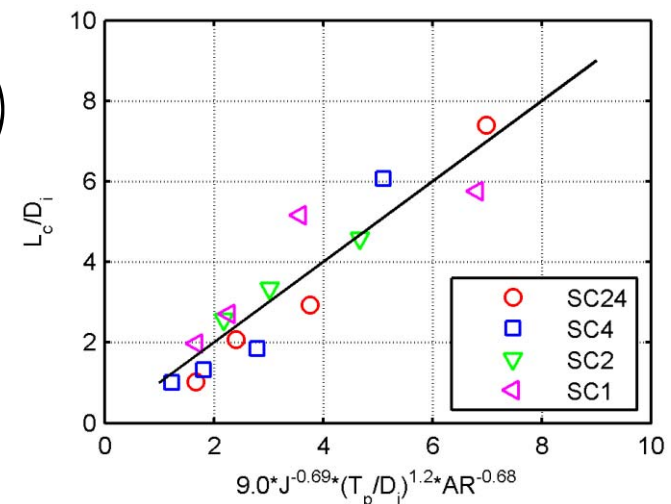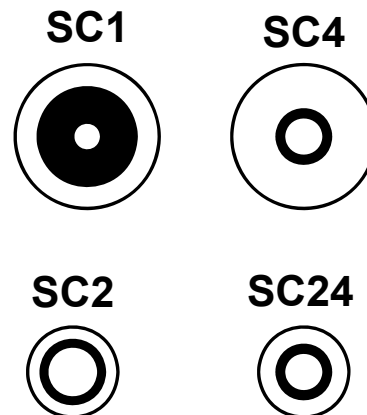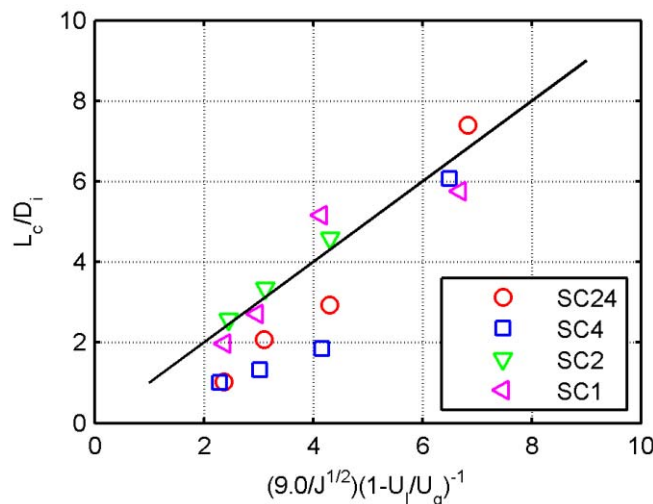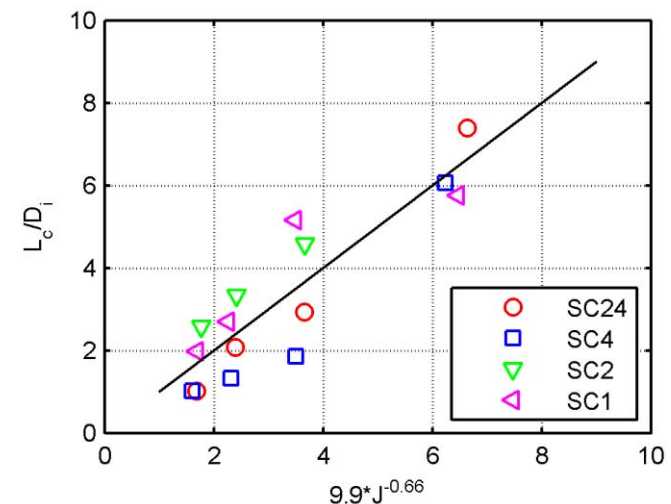- **Fit from Current Data**

  – $9.9J^{-0.66}$
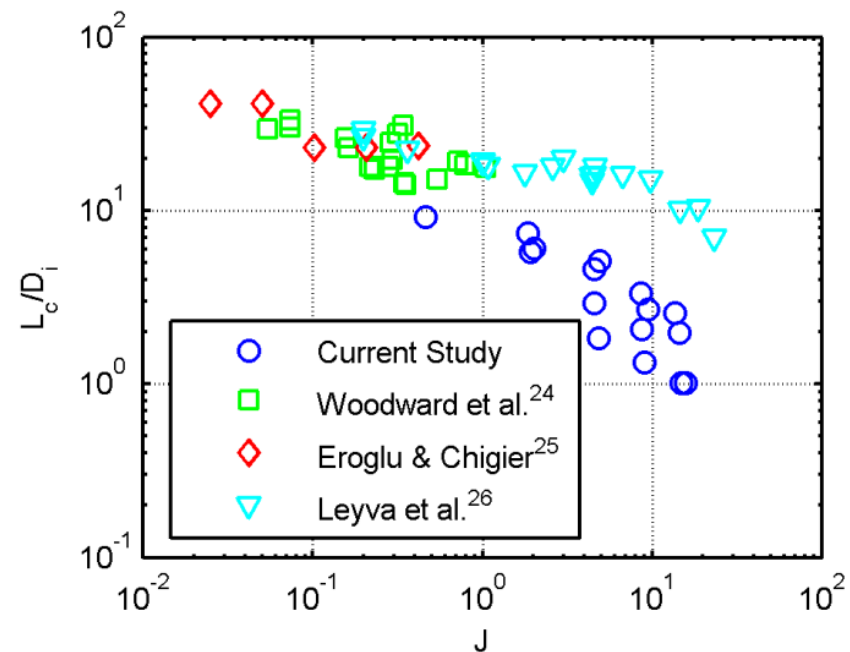
Scaling

- **Three core length scaling laws were investigated**

  - Standard momentum flux ratio

  - Momentum flux ratio with area and tip post ratio

  - Momentum flux ratio with velocity ratio

- **Linear regression used to fit constants and exponents for the momentum and momentum flux ratio with area and tip post ratio**

Summary & Conclusions

- **X-ray radiography was used to obtain quantitative EPL profiles in shear coaxial rocket injectors**
  - 4 injector geometries and 5 momentum flux ratio values were studied
- **All test conditions were shown to be in the fiber-type atomization regime**
- **Centerline profiles were used to develop four hypothetical atomization regions**
  - Near-Injector, Core Breakup, Transition, and Far-Field
- **Three methods were investigated to define core length**
  - Percent decrease, spatial derivative, and peak EPL RMS
- **Core lengths obtained using a 30% decrease in EPL and the peak EPL RMS were found to have excellent agreement**
- **Core length data was found to scale with $J^{-0.66}$ which differs from the $J^{-0.2}$ suggested by other two-phase shear coaxial jet investigations**
  - Difference in scaling likely do to differences in measurement technique
- **In the future backlit images of the current test conditions will be obtained so direct core length comparisons can be made**
- **Additional work is needed to further understand how the X-ray radiography technique compares with prior investigations**

Acknowledgements

- **A portion of this research was performed at the 7-BM beamline of the Advanced Photon Source, Argonne National Laboratory. Use of the Advanced Photon Source at Argonne National Laboratory was supported by the U. S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-06CH11357**

- **Special thanks for their assistance in setting up and data collection during the testing campaign at Argonne National Laboratory**

  - Todd Newkirk (Jacobs Technology, Inc.)

  - Earl Thomas (ERC, Inc.)

  - Larry Villasmil (Rochester Institute of Technology)

7-BM

Backup: Important Parameters

- ***EPL*** Equivalent Path Length, pathlength-integral of liquid in beam
- ***m*** Mass Flux Ratio, $\rho_l U_l A_l / \rho_g U_g A_g$
- ***Oh*** Ohnesorge Number, $\mu_l / (\rho_l \sigma_l D_l)^{1/2}$
- ***Re$_g$*** Gas Reynolds Number, $U_g (D_g - (D_l + 2T_P))/\nu_g$
- ***Re$_l$*** Liquid Reynolds Number, $U_l D_l / \nu_l$
- ***We*** Weber Number, $\rho_g U_g^2 D_l / \sigma_l$
- ***Φ*** Momentum Flux Ratio, $\rho_g U_g^2 / \rho_l U_l^2$